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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(b)(2).

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TITLE OF THE INVENTION (280 characters max)

Method to Reduce the Effect of Static Potentials in Capacitive Measurements

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Respectfully submitted,

SIGNATURE: [signature] Date: July 1, 2004

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PROVISIONAL APPLICATION COVER SHEET
Additional Page

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Method to Reduce the Effect of Static Potentials in Capacitive Measurements

Inventors: Robert Matthews, Paul Hervieux, Linas Kunstmanas, Igor Fridman

Date of Invention (concept/reduction to practice): November 3, 2003

Abstract.
A capacitive sensor is improved by reducing the signal artifacts that occur when it is operated in the vicinity of a static potential. A capacitive sensor so improved can be worn on the body to measure bioelectric signals such as ECG with increased comfort.

Field of the Invention.
Capacitive electrodes that sense the electric potential produced in the space surrounding a source[i] enable many important new measurement modalities. A particularly important new capability is measurement of bioelectric signals such as ECG and EEG without touching the skin, and even sensing through fabric. Almost all capacitive measurements that take place in the real word are degraded in some way by the presence of static electric fields. The subject of this invention is to reduce the effect of the local static field on a sensor or group of sensors used to measure a relatively small, spatially-localized, AC potential.

Background to the Invention.
An important and limiting factor in capacitive measurements is the ambient static electric potential at the region where the sensors must be located to measure the signals of interest. If this potential were true DC, i.e. it never changed, it would not be detected by a capacitive electrode. However, the static potential on an object can change — dramatically rising to levels of order 10,000 V due to triboelectric charging, and varying by significant levels due to discharging and the influence of other conducting bodies. In addition, motion of a capacitive sensor relative to the static electric field produces a change in the potential that is sensed. Such changes in the field can saturate the electrode, produce very large changes in its output necessitating a more complex data acquisition system to record the data, or mask the signal. Even at a low level, changes in the static field appear as measurement artifacts. Such artifacts can be very similar in frequency to the signals of interest, and are very difficult to filter.

In the more common resistively-coupled measurement of a potential, in which a low-impedance electrical contact is made with the object to be probed, the static potential on the object is relatively easy to control. For example, an electrocardiogram (ECG) taken in a hospital involves electrodes that attach to the skin via gel or adhesive to make an electrically conducting connection to the subject. When such connections are available, it is relatively simple to discharge static electricity on the subject using an additional resistive-contact ground strap, or to use the electrodes themselves. However, by its very nature, a non-invasive capacitive measurement system cannot make a DC-coupled electrical contact to an object, and therefore cannot reduce a static potential in this manner.

One method to facilitate a capacitive measurement is to allow the entire measurement system to float at the potential of the object. This approach minimizes the absolute potential difference presented to the sensor relative to the remainder of the sensing system. However, this approach is limited by how similar the potential of the sensing system is to the static potential of the object. For a system on the outer surface of the object with only capacitive coupling to that object, the system potential will always be different from the object, thereby producing a potential difference across the sensing region that could still be large compared to the signal of interest.

In theory, the static potential of the object could be removed by measuring the signal of interest with two or more electrodes and subtracting their outputs. However, this requires measuring a small signal in the background of a much larger signal, and taking the difference of two large quantities in order to discern a small quantity. Such a measurement is limited by unknown variations in the coupling of each sensor to the static potential, the calibration precision (gain and linearity) of the sensor components, and the dynamic range of the differencing system. While the latter two issues can be addressed at the expense of increased engineering cost and complexity, the former issue is a fundamental problem for capacitive sensors in a static field.

To minimize the variation in coupling to the static electric potential, the sensor can be positioned firmly against the subject. However, this approach runs counter to the objective of sensing the potential in a non-invasive manner, and is largely incompatible with incorporating sensors into clothing. A possible approach to couple to the signal in a reliable manner is to use a flexible resistive element attached to the electrode-sensing region. A way to do this was recently disclosed by Brun del Re and Batkin[ii]. This approach relies on maintaining an adequate resistive contact and, in the case of clothing, ensuring an adequate conductivity in the portion of the clothing that separates the electrode from the subject. Both of these requirements undermine the non-invasive aspect of the sensor.

Accordingly, there exists a need for a method or methods to reduce the effect of the background static field when making a high-sensitivity capacitive measurement of the electric potential in the vicinity of a object. This method should be compatible with the general concept of non-invasive capacitive sensing in that it must: a) not require a resistive contract to be established to the object at any point, and b) not rely entirely on preventing changes in the coupling of the electrode to the static field.

Summary of the Invention

The invention pertains to reducing the artifact signal coupled into a capacitive sensor when that sensor is operated in the static electric field produced by a local object. According to one aspect of the invention, a given static artifact can be reduced by minimizing the potential difference between the sensor circuit ground point and the potential of the object. According to a second aspect of the invention, the change in signal due to sensor motion in the electric field produced by the object is minimized by reducing the impact of changes in coupling to the signal source. Both of these aspects of the invention are compatible and, in general, can be used in conjunction.

The general measurement scenario is shown in Figure 1. An object 10 that is large compared to the spatial variation of the signal of interest is charged to a potential V_{static} relative to a distant point, which we define to be at zero potential. The conductivity of the object is such that the static potential at its surface is substantially uniform compared to the spatial variation of the signal of interest, and it maintains this spatial uniformity over the timescales of interest even when the static potential suddenly changes. An example of the object would be an aircraft, the human body, or a partly conducting shield placed over a sensor to protect it from the environment. The source of the signal of interest could be within the object (e.g. the heart in the case that the object is a human body) or produced outside the object (e.g. the field from a moving projectile). One or more capacitive sensors 30 are located sufficiently close to the object that the magnitude of the influence of the static potential at the point of measurement is comparable to the signal of interest.

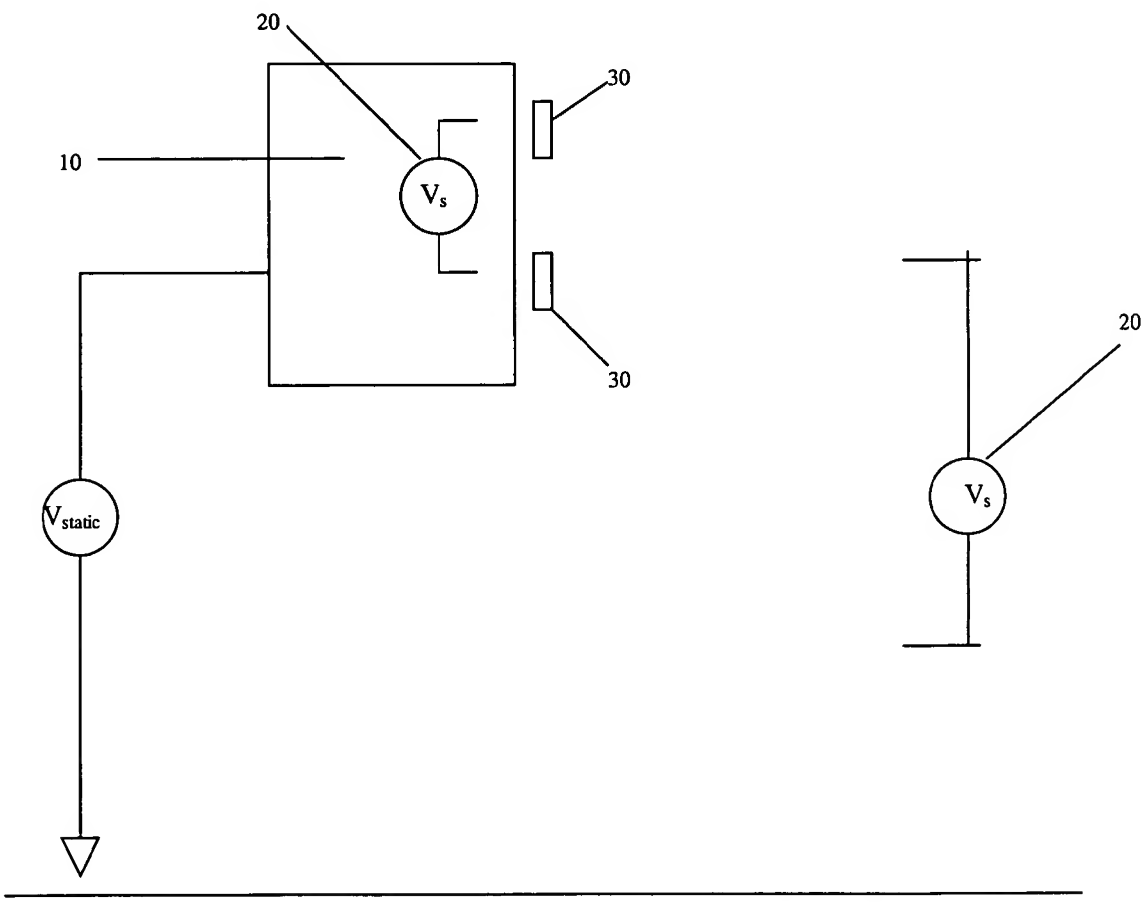

Fig. 1

The sensors can be located adjacent to each other at approximately the same distance from the object as shown in Figure 2, in line with each other in a direction away from the object as in Figure 3, or some combination of the two.

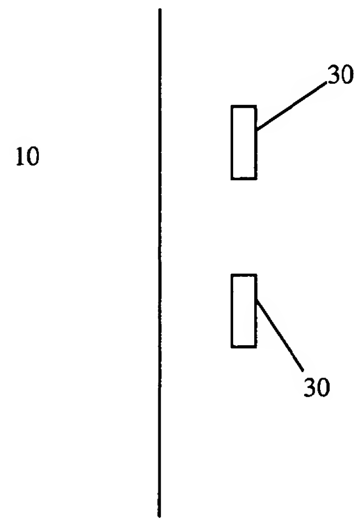

Figure 2

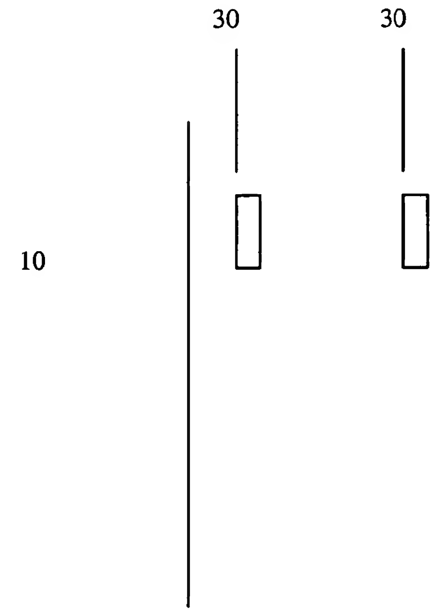

Figure 3

We define the static electric potential to be the large, almost constant potential produced by static electric charges on the object. These charges are usually produced by triboelectric phenomena. The static potential can be greater than 10,000 V and is extremely large compared to the signals of interest in many applications, which can be of the order 1 μV to 1 mV. A true capacitive sensor will not actually measure the static potential directly because the transfer function at DC is zero. However, changes in the static potential, ΔV_{static}, (due to, for example tribocharging or a change in the capacitance of the object to ground) are measured and can easily be greater than the maximum input range of the measurement electronics, which is typically less than $\pm$ 10V.

For simplicity, in the following discussion we consider the case of a measurement of a biological potential such as ECG or EEG on the human body. It will be appreciated, however, that the present invention applies to all cases in which one desires to minimize the effect of a large static potential on a sensitive measurement in a minimally invasive manner.

According to the first aspect of the invention, to reduce the potential difference in which the sensor must operate, the potential of the common point of the batteries (or other system) that provides power to the sensing circuit must be tied to the static potential of the object in some manner such that changes in the static potential are transferred to the common point. Typically the battery common point is referred to as the circuit ground, although, for the purpose of the

present invention, one of the voltage rails of the sensor circuit could be defined as ground instead. In conventional (resistive-contact) electrode systems, the sensing circuit is tied to the static potential using a ground strap or group of ground straps. For capacitive electrodes, grounding the battery system is much more difficult. One method is to place a relatively large object, such as the case holding the batteries, against the body in order to provide as large a capacitive coupling as possible[ii]. However, coupling of a capacitive system, especially one at close proximity to the body, is strongly affected by physical displacement relative to the body. As a result, a circuit ground made in this manner is vulnerable to motion artifact and does not in general track the static potential accurately. The less firmly attached to or further away from the body the capacitive ground is, the less the influence of the static potential is minimized in the measurement.

One embodiment of the invention that reduces the effect of the static potential difference between the sensor circuit ground point and the sensing region of the electrode is shown in Figure 4. The method works by sensing ΔV_{static} using an independent electrode. The output of this electrode drives the ground of one or more sensors used to sense the source of interest.

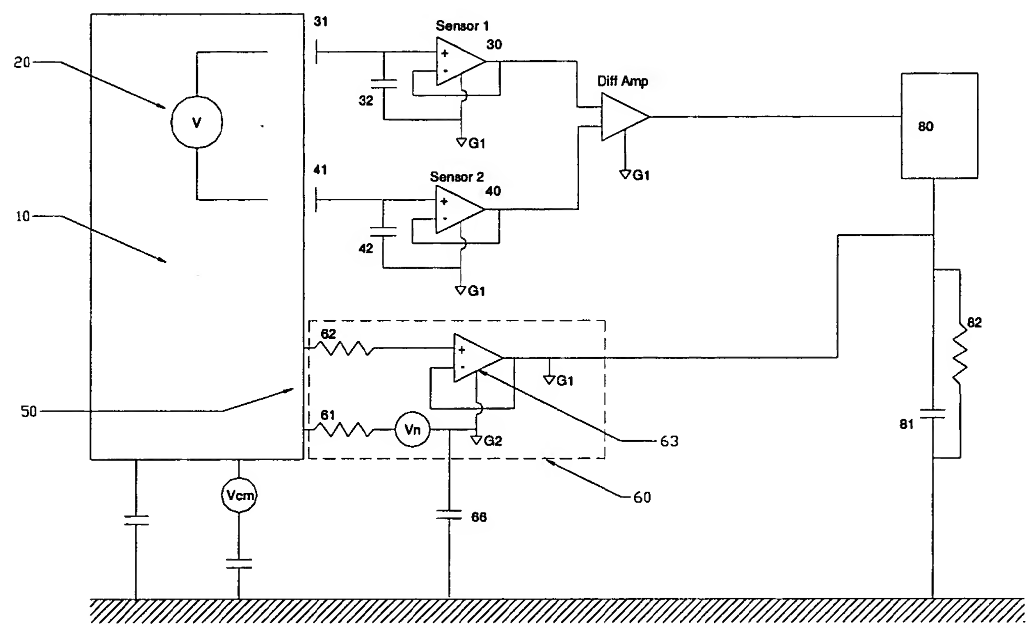

Figure 4: ECG System Equivalent Circuit with Ground Sensing Circuit

The detailed operation of this circuit is as follows. A nominal ground connection 61 is made to the object of interest at a location 50 where the signal of interest is expected to be small. The ground can be made by a weak resistive connection (e.g. a dry metal electrode on the skin), or a capacitive connection implemented via a conducting fabric or simple conducting surface against the skin that is electrically insulated from the skin (only the resistive form of the connection si shown in Figure 4). The important point to note is that the connection from the nominal ground to the battery common has low electrical impedance. A similar coupling to the body 62, termed the ground-sensing electrode, is made at a point close to the nominal ground 61 using an identical conducting material. In contrast to the nominal ground, the potential of the ground-

sensing electrode is measured by an amplifier 63 with very high impedance (of order 1 TΩ). The function of the ground-sensing electrode is to measure the static potential of the body.

We term the circuit comprised of the nominal ground and the ground-sensing electrode the ground-sensing circuit 60. The output of the ground-sensing circuit drives the battery common 70 of the sensors used to measure the signal of interest. The result is to minimize the static-induced potential difference across the input of the sensors.

The ground-sensing circuit 60 can be understood via the following argument. Ideally the battery common VG2 of the ground-sensing circuit would be at the same potential of the body. However because the connection 61 of the nominal ground to the body is poor, the battery common will not in general be at the body potential, but rather at some intermediate potential between the body and other objects around it. As a specific example, consider a sudden change in static potential, ΔVstatic, of 20 V, and a change in the voltage of the battery common of the ground-sensing circuit of 15 V. The reason why the battery common voltage differs from ΔV_{static} is because of the potential divider network formed by the impedance of the nominal ground to the body, and the capacitive coupling 66 of the ground sensor circuit to its local environment, which is taken to be a zero voltage relative to the body potential. As noted, the ground-sensing electrode 62 is connected to a high-impedance amplifier, and so the potential presented at the input to the ground-sensing circuit is very close to ΔVstatic, say 19.9 V in our example. The amplifier 63 is connected in a voltage follower configuration, and so the output VG1 of the ground-sensing circuit 19.9 V – 15 V = 4.9 V relative to its nominal ground of 15 V. As a result the output of the ground-sensing electrode is 19.9 V, very close to ΔVstatic of 20 V.

The ground-sensing circuit output can be used to control the grounds of the sensor or sensors used to measure the biological potential or potentials of interest. It can also be used to drive the ground point of subsequent filtering and data acquisition stages, thereby allowing such stages to have larger electric coupling to their environment than would otherwise be possible. For example, a battery powered acquisition system placed on a desk will typically be at a significantly different instantaneous static potential than that on a human body within 1 m of it. Such a large difference can push the sensor output outside the dynamic range of the acquisition system and introduce artifacts. By driving the ground point of the acquisition system via the output of the ground-sensing circuit, such problems and artifacts can be significantly reduced. This capability enables capacitive electrodes to be coupled to recording systems not located on the body.

The ground-sensing circuit is able to produce a potential that matches the change in static potential very closely provided the voltage drop across the nominal ground connection 61 is less than the output voltage that can be produced by the ground-sensing circuit. This output range can be increased by additional amplifiers and larger voltage rails, but in general a range of –10 V to + 10 V is adequate for use on a clothed human body.

It should be further appreciated from the discussion above that the performance of the ground sensing circuit can be improved, or the requirements on it alleviated, by reducing the generation of static electricity by the sensors rubbing on the skin, and or by reducing the capacitive coupling 66 of the system to the local environment. Methods to reduce the former include using coatings

on the sensor that minimize the generation of static electricity when the sensors are rubbed on the body or on fabric, using static minimizing coatings on fabric against the body or the sensor, and separating the sensor from the body to minimize direct rubbing.

Methods to reduce the capacitive coupling of the system to the environment focus on reducing the system size. One method is to power both the ground sensing circuit and the sensors themselves from a single battery or power supply. To do this the power source must use inductive or capacitive isolation to drive separate circuits that are decoupled from each other at the frequency of interest. Another method to reduce system size is use sensor components optimized to reduce power, thereby allowing the use of a very small battery. Yet another method is to use sensors that only swing in voltage from zero to either positive or negative voltage, thereby reducing the number of cables linking the sensor to the rest of the system from three to two.

Another method of reducing capacitive coupling of the system to the environment to improve the performance of the ground sensing circuit, or reduce the requirements on it, is to locate one or more components of the system off the body and link them to the on-body sensor suite via a wireless link. Such a link can transmit analog or digital information and therefore allow data acquisition, data storage and data display systems to be located off the body. Such an approach removes the effect of the capacitance 81 in coupling the sensor system to the environment.

One issue in the practical operation of a sensor system incorporating a ground sensing circuit occurs if the object 50 is coupled with a low impedance in some manner to the ground of the data acquisition system 80. Such a ground could occur if the system 80 is housed in a conducting case that touches the body, or if the acquisition system is also used to collect date from another sensor or system that establishes a low impedance contact with the object. When such a ground occurs the a current flows down the output VG1 of the ground sensing circuit to the data acquisition system 80 and back to the body. This current can be reduced to negligible levels by incorporating the modification shown in Figure 5. In this embodiment of the system, the output of the ground sensing circuit, VG1 is not connected directly to the ground of the data acquisition system 83 as in Figure 4, but instead the ground 83 is driven by the difference between VG1 and the difference in the sensor outputs.

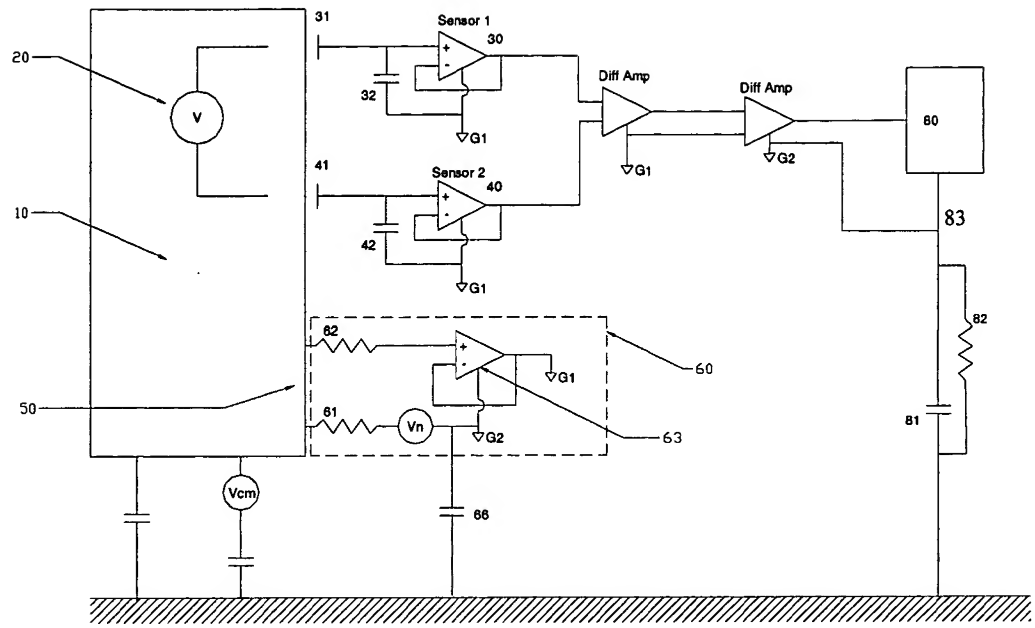

Figure 5. Form of the System Shown in Figure 4 with a Modification to Minimize Current in VG1 in the Case that the Data Acquisition System has a Separate Low Impedance Path to the Object Being Sensed.

A method to minimize the current flow to the body in all circumstances is to place resistors in series with the ground sensing electrodes 61 and 62, and the coupling capacitances 31, 41 and the inputs to the amplifiers 30, 40, and in series with any guard circuits that have appreciable coupling to the body. The addition of the resistors in these paths limits the current flowing to the object in the case of faults in the sensor. This feature is particularly useful in the cases in which the sensors are used to measure signals from the human body.

Figures 4 and 5 show two capacitive sensors being used to collect the signal of interest. Taking the difference of two sensor measurements is standard practice in many applications (for example the lead configurations used to diagnose heart ailments in ECG). Provided the static potential does not exceed the measurement range of the sensors, it can in theory be removed to a very large extent by taking the difference in sensor outputs. This approach works relatively well for conventional skin-contacting resistive electrodes, but works less well for capacitive electrodes, particularly for ones that are not firmly attached to the body. The reason is lack of precision and repeatability in the coupling efficiency of a capacitive sensor to the static potential due to changes in the capacitance of the electrode that couples to the potential. If the fraction of the static signal coupled into two different sensors is different, then subtracting their outputs will not cancel the static signal, even if the sensors are identical. Accordingly, a second aspect of the invention to reduce the effect of a static potential is to make the signal measured by a capacitive electrode less susceptible to differences in the electrode capacitance.

The variation in coupling efficiency can be understood as follows. The signal presented at the input of the first stage amplifier of a capacitive sensor is determined by the potential divider network comprised of the electrode capacitance and the input capacitance of the amplifier. On the human body, variations in the electrode capacitance can occur due to inhomogeneities in the thickness of the outer skin layer, variations in the thickness of clothing between the electrode and the subject, and relative motion between the electrode and the subject

One method to reduce the relative effect of these variations in coupling to the static field, and an aspect of the present invention, is to insert a series capacitor between the electrode and the amplifier. Similarly, a second aspect of the invention is to increase the distance of the sensor from the body. This has the effect of adding a series capacitance and therefore also reduces the dependence of the coupling efficiency on the electrode capacitance. Yet a third aspect is to wet the region between the sensing surface and the body with a mildly conducting fluid in order to reduce variations in the electrical properties of the outer skin layer, and clothing if present. However, when used on the human body, the first two of these measures degrade the signal collected by the sensor, and to that extent are inefficient in their removal of the artifacts due to the static field. The third method is in general cumbersome to implement and goes against the general goal of a minimally invasive interface.

An improved method that can be used alone or in conjunction with one or both of these other two methods is to modify the sensor circuit itself so that it is less susceptible to differences in the coupling of the electrode to the body.

The simplest form of the sensor circuit is shown in Figure 6. The capacitor Cin represents the coupling between the electrode and the body, Ca is the amplifier input capacitance, and Ra the combination of amplifier input resistance and shunt resistance added at the amplifier input to stabilize it with respect to its bias current. The amplifier and value of Ra can be selected so that over the range from approximately 0.1 Hz to 50 kHz the effect of Ra on the circuit transfer function is negligible. The functional form of this circuit in this regime is shown in Figure 7. In this regime where Ra can be neglected, the fraction of the signal, η coupled into the amplifier input is given by the ratio: $\eta = Cin/(Cin + Ca)$.

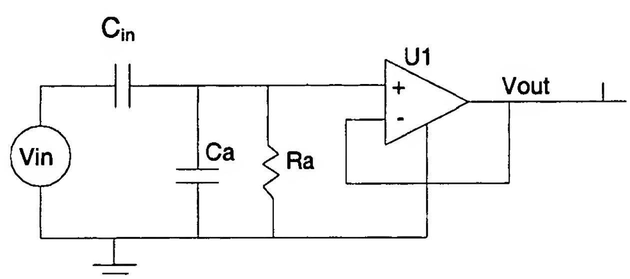

Figure 6. Simplest Form of a Capacitive Sensor Circuit

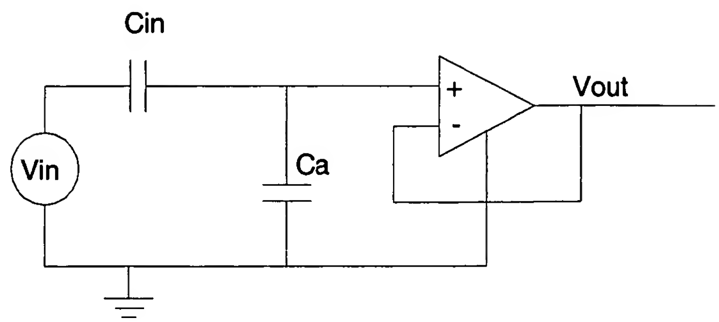

Figure 7. Functional Form of the Capacitive Sensor Circuit in Figure 6 Over the Operating Frequency Regime

A modified form of the basic sensor circuit that has the improved property that η is less susceptible to changes in Cin is shown in Figure 8. In this circuit, a current is fed back into the amplifier input to cancel the current that flows into the amplifier. This feedback has the effect of reducing the effective value of Ca, is generally known as negative impedance converter[iii].

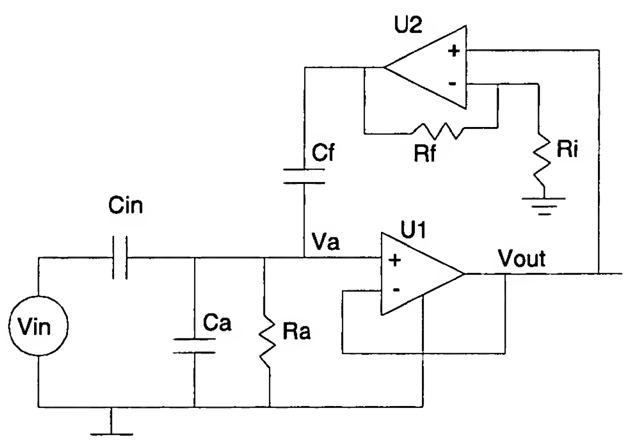

Figure 8. Feedback Circuit Added to the Basic Sensor Circuit to Reduce the Effect of Variations in Cin

In the circuit of Figure 8, the efficiency is given by:

$$\eta = \frac{V_{out}}{V_{in}} = \frac{Vin * Cin}{Cin + Cf + Ca - G * Cf}$$

where G is the gain of the feedback path and can be adjusted via the feedback resistor Rf. If G is tuned to equal 1 + Ca/Cf , η = 1, and more importantly does not depend on the value of Cin. Using this approach, a cancellation of 99.9% of the static signal can be achieved between two capacitive sensors, even through clothing.

Claims

What is claimed is:

1. A sensor system for measuring the electric potential via capacitive coupling comprised of:
   a. An electrode that couples to the local electric potential, serving to sense said potential,
   b. A high-impedance amplifier connected to said electrode configured to buffer the potential of said electrode and output it to subsequent low-impedance circuits,
   c. A means to reduce the effect of a change in the local static potential on the measurement of interest.

2. A system as in claim 1, in which the means to reduce the effect of a change in the static potential on the measurement of interest is a circuit that senses the local static potential and drives the ground point of the sensing element or elements of said sensor system potential to the value of the local static potential.

3. A system as in claim 1, in which the means to reduce the effect of a change in the static potential on the measurement of interest is the method as of claim 2 combined with an additional means of a capacitor inserted in series between the electrode and the high-impedance circuit, and in which the effect of this capacitor is to make the fraction of the potential at the electrode that is coupled into the amplifier less sensitive to the capacitance of the electrode.

4. A system as in claim 3, in which the additional means to reduce the effect of a change in the static potential on the measurement of interest is an increase in the separation between the electrode and the source of the static potential.

5. A system as in claim 3, in which the additional means to reduce the effect of a change in the static potential on the measurement of interest is to wet the region between the sensor and object being measured with an electrically conducting fluid.

6. A system as in claim 1 in which the means to reduce the effect of a change in the static potential on the measurement of interest is a feedback network comprised of an amplifier and series capacitor in which the gain of said amplifier is set to 1 plus the input capacitance of the said high-impedance amplifier connected to said electrode divided by the value of the series capacitor of the feedback network.

7. A system as in claim 1, in which the means to reduce the effect of a change in the static potential on the measurement of interest is the method as of claim 6 combined with an additional means of a capacitor inserted in series between the electrode and the high-impedance circuit, and in which the effect of this capacitor is to make the fraction of the potential at the electrode that is coupled into the amplifier less sensitive to the capacitance of the electrode.

8. A system as in claim 7, in which the additional means to reduce the effect of a change in the static potential on the measurement of interest is an increase in the separation between the electrode and the source of the static potential.

9. A system as in claim 7 in which the additional means to reduce the effect of a change in the static potential on the measurement of interest is to wet the region between the sensor and object being measured with an electrically conducting fluid.

10. A sensor system according to claim 1 in which any combination of means to reduce the effect of a change in the static potential as described in claims 2 to 9 is used.

11. A sensor system according to claim 1 and any combination of the claims 2 to 10, in which more than one electrode and high-impedance circuit combination are used to sense the potential of interest.

12. A sensor system according to claim 1 and any combination of the claims 2 to 11, in which the potential of interest is produced by a biological entity.

13. A sensor system for measuring the electric field via capacitive coupling comprised of:

   a. An electrode which couples to the local electric potential, serving to sense said potential,
   b. An amplifier of impedance greater than 100 MΩ connected to said electrode and configured to transduce the potential of said electrode to subsequent low impedance circuits,
   c. A means to reduce the effect of a change in the local static potential on the measurement of interest.

Repeat of subsidiary claims to claim 1.

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[i] Krupka, Michael Andrew, Low Noise, Electric Field Sensor US Patent Number 6686800 B2
[ii] "Enhanced Pickup Electrode," WO 02-065905 A1
[iii] Horowitz and Hill, The Art of Electronics, second edition, page 266